Model Predictive Control for Automotive Applications in off highway

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Doctor of Philosophy

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Introduction

Model Predictive Control (MPC) is state of the art and widely accepted methodology in process industry as well all other domains like aerospace, automotive, robotics etc. It is an optimization-based control method for multi-input and multi output systems (MIMO) which includes physical and operational constraints. It is one of the control methods which directly considers constraints. It is a plant model-based control strategy which gives optimal control when plant model with enough accuracy is provided. At each time sample, the optimization problem is solved to get the optimal control action. The optimization function is formulated to reduce the error between reference input and measure plant output. Hard constraints on plant inputs like actuators and soft constraints on output can easily accommodated in optimization problem. If the optimization problem becomes infeasible to solve, the constrains can be relaxed using slack variables. The effort required for tunning the MPC controller is same for MIMO and single input and single output (SISO) systems which results in shorter development time. The receding horizon method to solve finite horizon optimal control problem requires online solution at each discrete sampling instant which requires higher computational power. MPC can even control systems which cannot be controlled by classical controls due to its predictive action based on plant model.

Asymptotic stability of LTI system using MPC with hard input constraint and soft output constraint over finite horizon is guaranteed when optimal cost function of the MPC is monotonically decreasing over time[2]. The potential of MPC not solely based on prediction but also on the fact that it can be used for non-linear models. Various MPC controller designs like gain scheduling, adaptive, non-linear, explicit are available today.

Disturbance rejection can be effectively handled by MPC. The input measured and unmeasured disturbances can be accommodated in the controller design. In most of the control applications, the measured data contains noise and this sensor noise can be modelled to provide effective disturbance rejection and improve robustness. The plant model or system also contains the process noise. Even this process noise can be modelled in the MPC design process. Due the adaptability of various disturbances and noise, the MPC has popularity of being a control method which can run long time without expert intervention. Tunning of MPC is being done by modify the weights assigned to cost function, prediction horizon and control horizon lengths.

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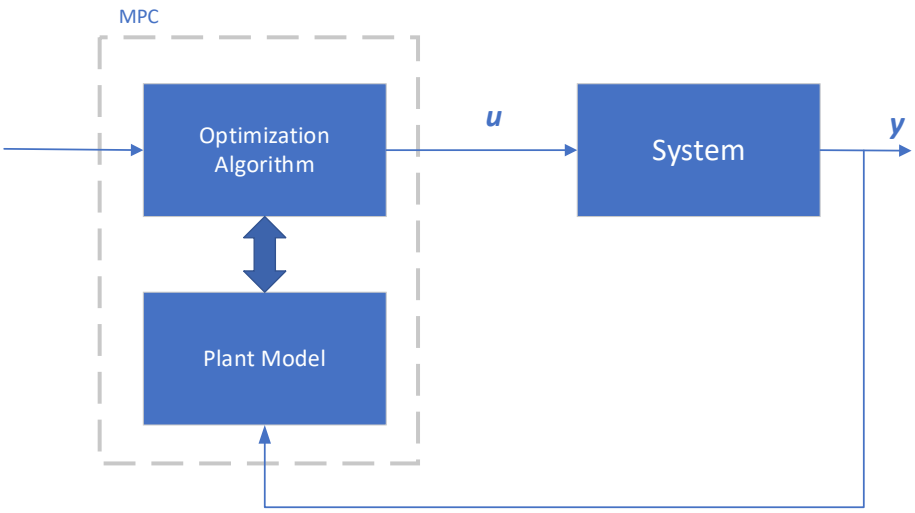

Figure 1 Simple block diagram of MPC control

Explicit MPC has advantage of solving optimization problem offline. This reduces the computational overhead in sample time and addresses issues of software certifications caused by numerical solvers in safety critical applications. To reduce the complexity of explicit form, a suboptimal solution of optimization problem can be found [3].

First application of MPC applied on process control industry due to inherent nature of open loop stability and large sampling time [1]. Due to recent advancements in processing power of microcontrollers, the realization on embedded hardware is becoming feasible and MPC can be seen applied in not only in process industry but also in various other domains like automotive, power electronics, climate control, manufacturing, aerospace etc. Automotive applications have complex system dynamics due to varying load conditions and non-linear nature of different components like tire, transmission etc. Also due to strict safety regulations, the controller designed should stable with faster time response. Different applications of MPC in on highway vehicles like vehicle stability control, wheel slip control, anti-jerk control can be found in [7]. Also due to the promising results of MPC, it has also been applied in off highway vehicles to control vehicle stability, wheel slip, cab suspension etc.

Various software tools available in today to evaluate design of MPC controller like MATLAB Model Predictive control toolbox. Input and output disturbances (measured and unmeasured) can be easily added the MPC controller. MATLAB MPC controller has inbuilt state estimator to estimate the states but a custom estimator also can be designed to use with MPC controller. MPC toolbox has linear MPC

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controller, gain scheduling, adaptive, non-linear MPC controller etc. Even to reduce the computation overhead the explicit MPC controller also being supported in toolbox. Another open source toolbox developed by Moritz Diel called ACADO is being used for MPC as well as for state estimation.

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Problem Statement

The main of focus of the Model Predictive control for automotive applications are summarized below.

Off road vehicles has uncomfortable ride performance if it is not equipped with active suspension due to rough road surface. Large horsepower off road vehicles like tractors have today equipped with different types of suspensions like front axel, cab suspension etc. These suspensions are controlled electronically using different types of control algorithm. Due to the nature of complexity, the system becomes multi-input and multi output (MIMO) with constrains on inputs. Model predictive control can be used to control the oscillations.

Other application of MPC can be effectively utilized in Energy Management in Hybrid Vehicles (HEV). HEV has power generation devices like engine, motor, generator and energy storage devices like fuel tank, battery, fly wheel etc. The objective is to minimize the fuel consumption subject to charge constraints of battery.

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Literature survey

Model Predictive Control requires formulation of optimal control problem based on plant model defined and based on estimated states using state estimator, the optimal control action at every sample is being calculated. After applying the control action, the action is again being calculated based on plant outputs and this goes for every sample. Due to the computation effort required and usefulness in mainly MIMO system, the first application being applied in process industry [1].

Ride comfort in off highway vehicles play important role due to operations of vehicle in uneven terrain and long run of operations. C. Poussot-Vassal and others [8] simulated the semi-active suspension system for single corner model using MPC with different tunning parameters and the performance is evaluated using ride comfort cost function. Zhang Houzhong and others [9] applied explicit model predictive control to full car model to address the fast dynamics of the system. Results show that the explicit model predictive control performance is as good as traditional MPC and saves considerable computation time. Charles Poussot-Vassal and others [10] put ride comfort and ride handling cost function to evaluate different control strategies for semi active suspension. The equations presented in terms of cost function can be used to benchmark the control methods. To evaluate the ride comfort quality, the methodology for performance matric is developed in ISO 2631 by International Standard Organization [11].

HEV needs efficient energy management to meet dynamic torque demand. Chao Sun, Xiaosong Hu [12] used three different types of velocity predictors to apply supervisory MPC for energy management in power split HEV. Seyedeh and Baisrava [13] uses MPC as short term and long-term decision making by incorporating the bounded uncertainties in the future torque and velocity demand. The simulation results showed the fuel efficiency improvement over traditional approach with charge balance constraint.

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Methodology

Automotive control systems are safety critical and require fast dynamic response. It also has constraints on inputs and outputs. Due to discrete architecture of different controllers located at different locations, the control systems are independent with each other. And it is necessary to have sometimes a supervisory control to satisfy goals overall to vehicle.

This work addresses couple of control applications specific to off highway vehicles using Model predictive control. First is the cab suspension control using full car model with cab mounted on chassis. The mathematical plant model for this architecture needs to be carried out and multi input multi output state space model needs to be derived. This work have two plant models linear and nonlinear and compare the control strategy using Model predictive control for linear and non-linear systems.

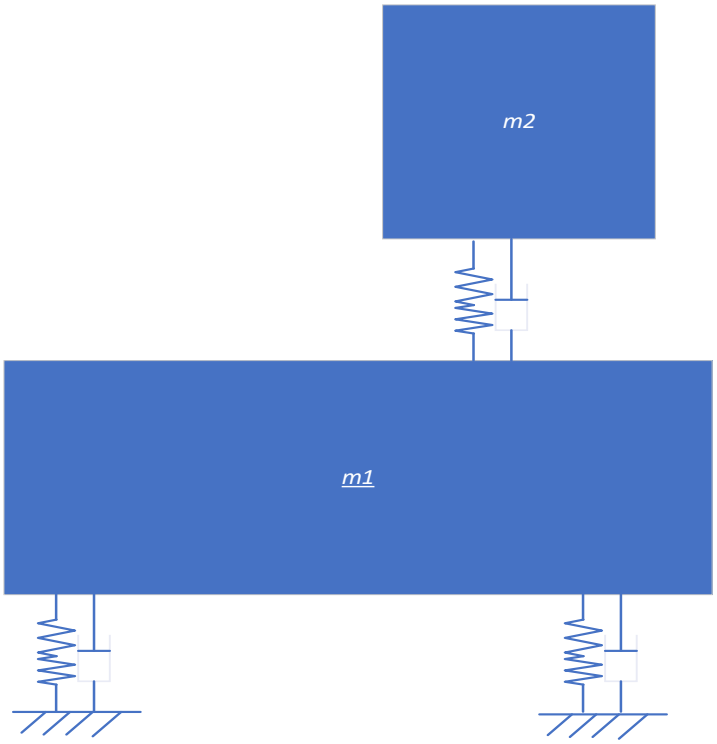

Figure 2 Simplified Cab suspension system

Further, the result of model predictive control with online optimization against explicit model predictive control will also be compared for real time control application.

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Second application in off highway vehicle is for energy management in hybrid vehicles. Unlike on road vehicles, there are various sources and consumers of energy in off highway vehicles. The effective energy management is necessary to achieve optimal power usage since there are more energy consumers like Power Take off (PTO), Rear Hitch, Front hitch, Air Conditioning etc. Model predictive control can be used to act as a supervisory control to fulfill the demand of each consumer and to save fuel consumption.

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